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## High Power Density Carbon Neutral Electrical Power Generation for Air Vehicles

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### Project Vision















*“We are solving the electrification of aviation by integrating the propulsion, power, and thermal systems for an energy optimized aircraft.”*



Range Extenders for Electric  
Aviation with Low Carbon and  
High Efficiency (REEACH)



# Team

	Team member	Location	Role in project	
	Rory Roberts, Tennessee Tech University	Cookeville, TN	Project Lead, System design lead -18 years experience in SOFC technology - Integrated propulsion, power, thermal expert	
	Ted Ohrn, Special Power Sources	Alliance, OH	SOFC tube and stack design-Lead -30 years experience in SOFC's	
	Roland Dixon, Special Power Sources	Alliance, OH	Technology Transfer and Outreach-Lead -40 years government PM experience	
	Chuck Lents, Raytheon Technologies	East Hartford, CT	Turbo-machinery & generator – Lead • 35 years in aircraft integrated system • RTRC electrified propulsion research lead	
	Kashif Nawaz, Oak Ridge National Lab	Oak Ridge, TN	Fluid-thermal modeling and design -Expert in high temperature thermal mng.	
	John Hull, Boeing	Seattle, WA	Integration with aircraft	
	Mitch Wolff, Wright State University	Dayton, OH	Turbogenerator integration -Jet engine expert	

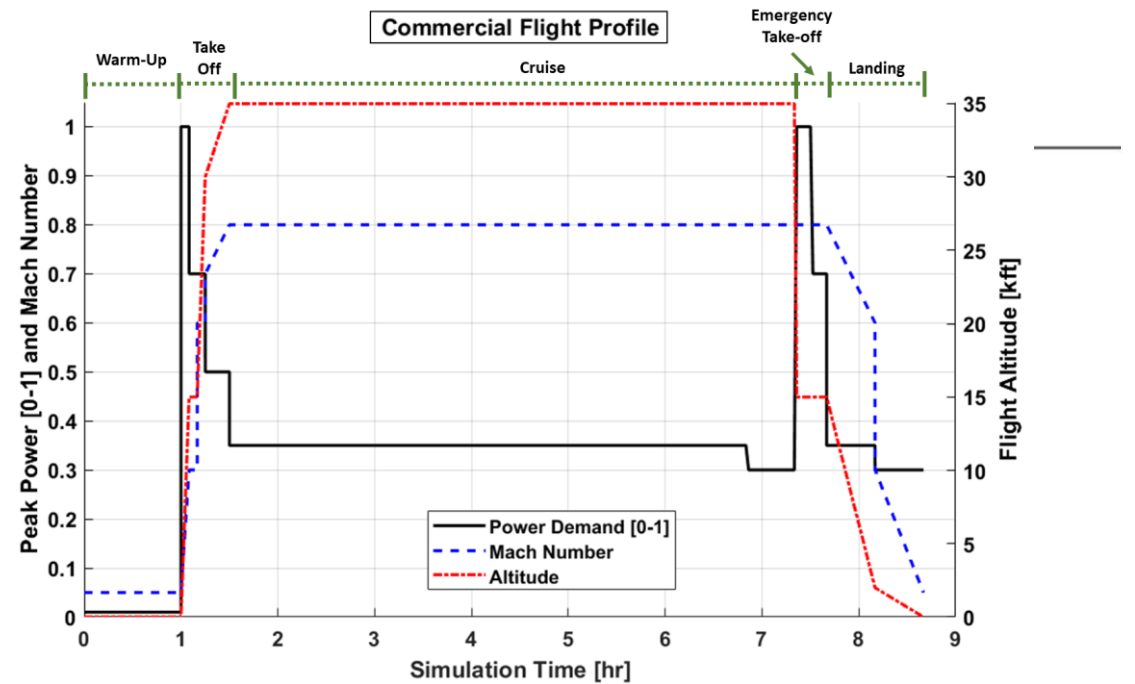
# Large Scale Electric Propulsion Approach

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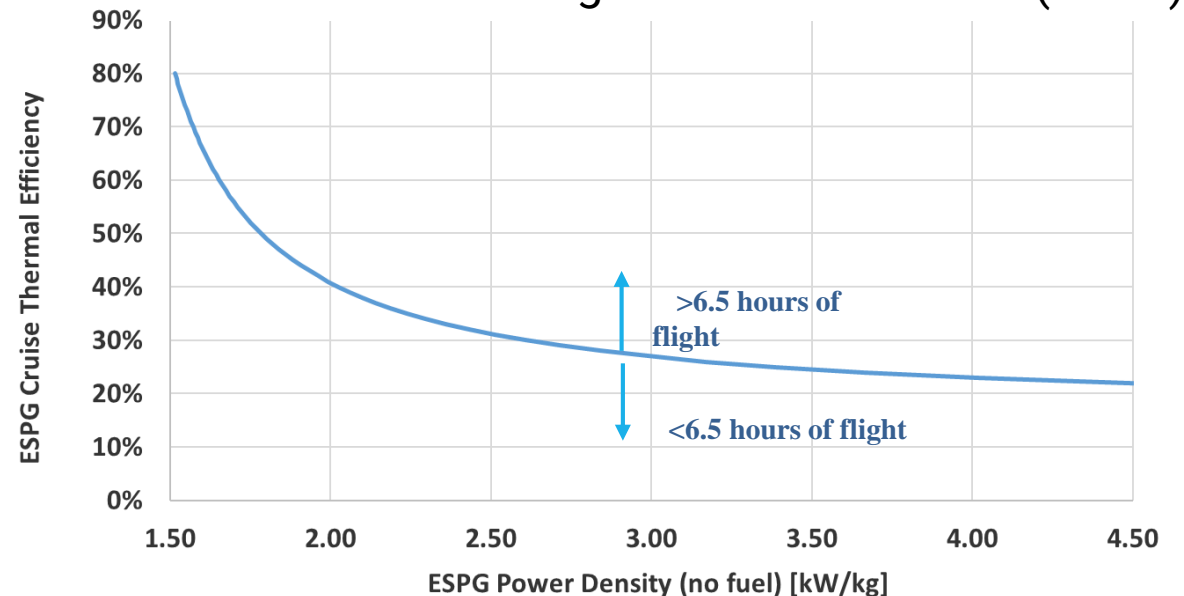
- ▼ Requires high conversion efficiency to drive down:
  - \$/passenger mile
  - Net zero Emissions
  - Meet current fuel storage requirements
- ▼ Vehicle level top-down design approach is required
- ▼ Reliability in approach for aerospace standards
- ▼ High power density electric centric systems:
  - Electric power production (REEACH)
  - Electric propulsors (ASCEND)
  - Electrical distribution system (CABLE)
- ▼ Manage 100's kW's of thermal management

# REEACH ESPG Requirements

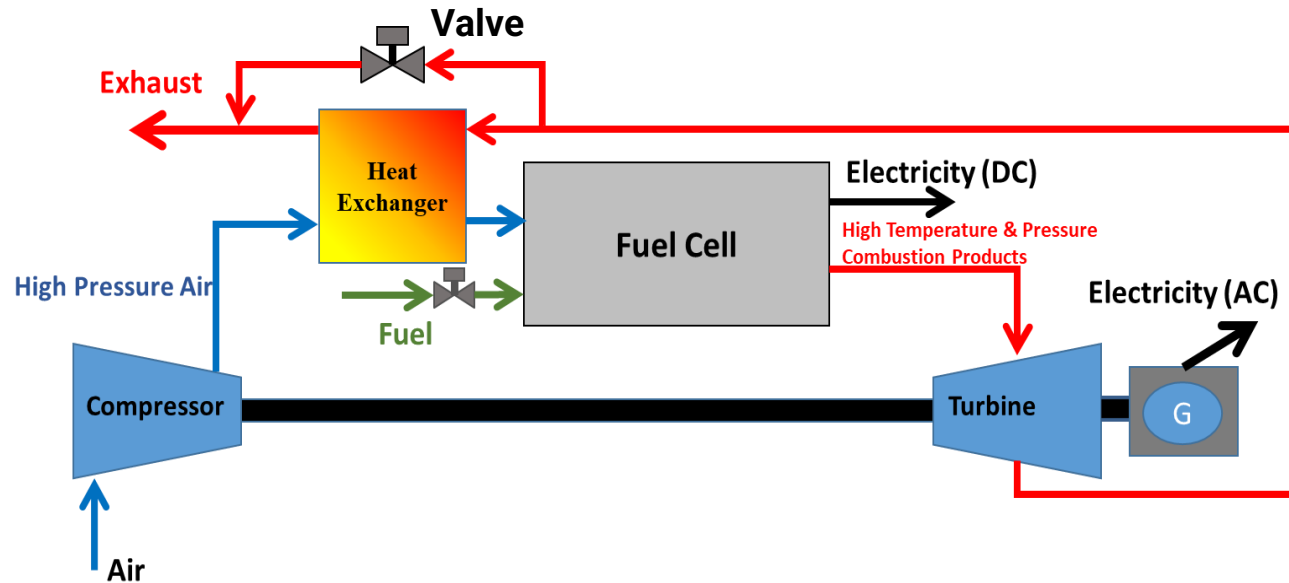
- ▼ 28.7 MW Take-off Electrical Power
- ▼ 8.5 MW Cruise Power
- ▼ > 3 kW-hr/kg
- ▼ <0.15 \$/kWh
- ▼ ESPG < 25,804 kg (includes fuel)
- ▼ 6.5 hours Flight time
- ▼ Ambient Temperature range, -54° to 30°C
- ▼ Ambient Pressure range, 23 kPa to 101 kPa
- ▼ Initial Targets
  - ESPG > 1.12 kW/kg
  - SOFC-C-TG > 1.6 kW/kg
  - At 65% ESPG Efficiency



## Electrical and Storage Power Generation (ESPG)



# Conventional Fuel Cell-Gas Turbine Hybrid (FC-GT)



## Pros

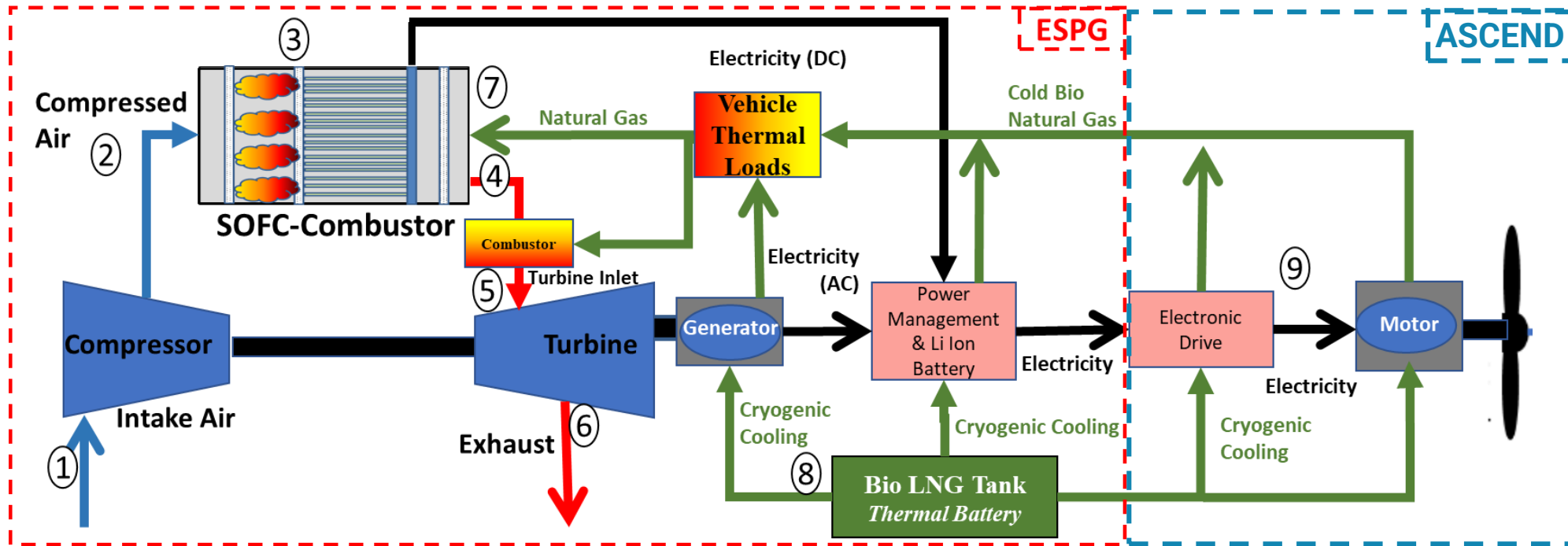
- FC-GT provides ultra high chemical-to-electrical conversion efficiency
- Provides pressurized environment at high altitudes

## Cons

- Large massive systems with low specific power
- Large thermal mass, sluggish response to perturbations
- Long cold startup times
- Complex thermal management of fuel cell typically with large valves

# Proposed Integrated ESPG Concept

Solid Oxide Fuel Cell Combustor-Turbogenerator system (SOFC-C-TG) is proposed for the ESPG



## Pros

- SOFC-C-TG provides a simple & elegant solution for electric power generation in air vehicles
- SOFC-C-TG eliminates cathode heat exchangers, large thermal mass. **Minimum size and weight**
- Provides precise thermal control of SOFC stack at cathode inlet. **Minimum use of valves**
- Rapid response to perturbations and extreme conditions: load, inlet temperature and pressure.
- Redundancy and reliability

## Cons

- New concept, never been fully demonstrated

# Vehicle Level Transient Analysis

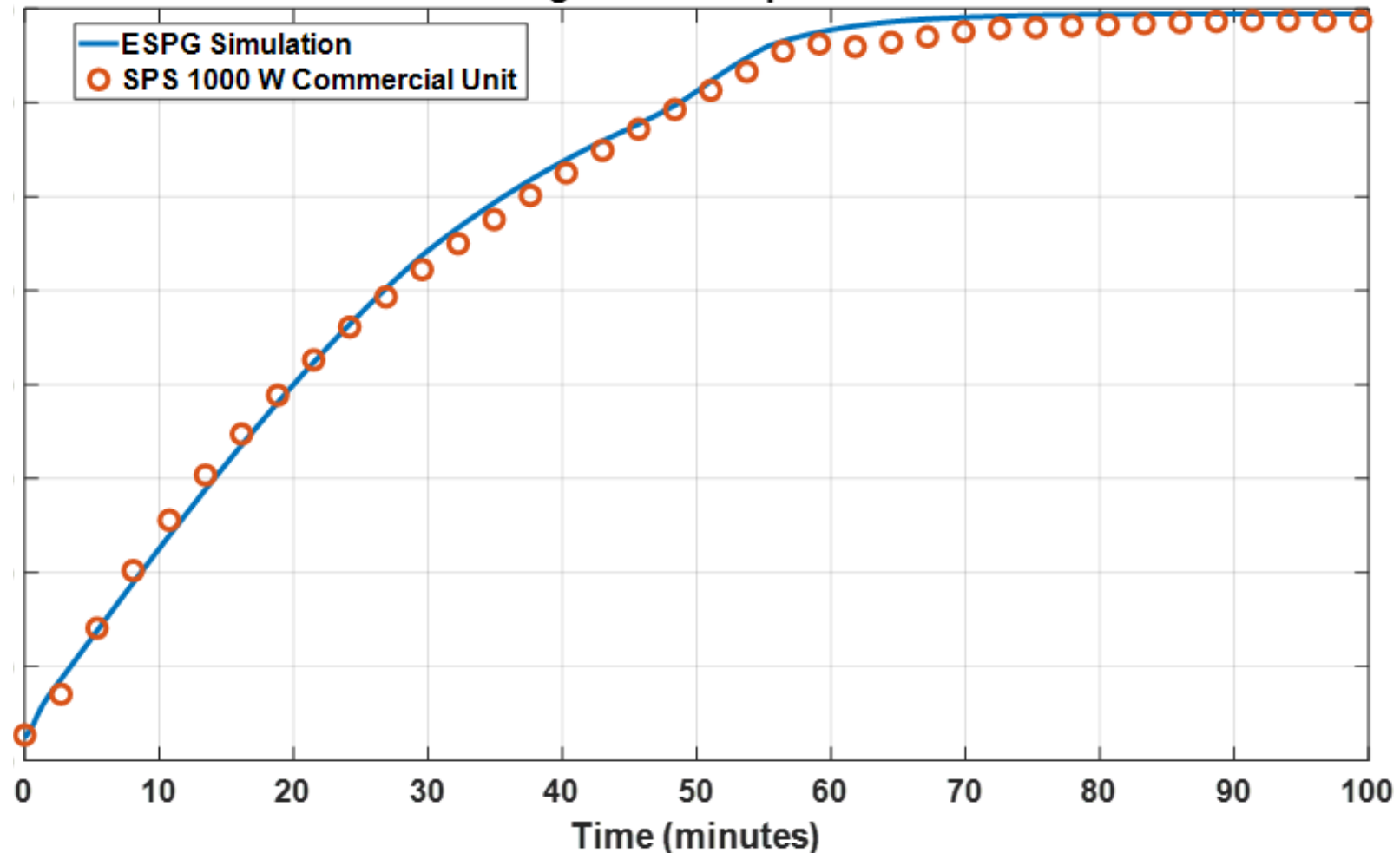
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- ▼ ESPG model integrated with a notional 737 Boeing class aircraft
  - Objective: To establish detailed boundary conditions and required operational characteristics of the ESPG components
  - MATLAB/Simulink detailed transient model with vehicle level controls
    - Quasi-2D SOFC : electrochemistry overpotentials, reformation and electrochemical kinetics, heat transfer included
    - TG includes: performance maps, shaft dynamics, unsteady flow
    - Combustors: combustion reaction and products, heat transfer
    - Electrical Power Conditioning System: Vehicle electrical load balance and control
    - Fuel Thermal Management System: bio LNG tanks, fuel heat exchangers, valves

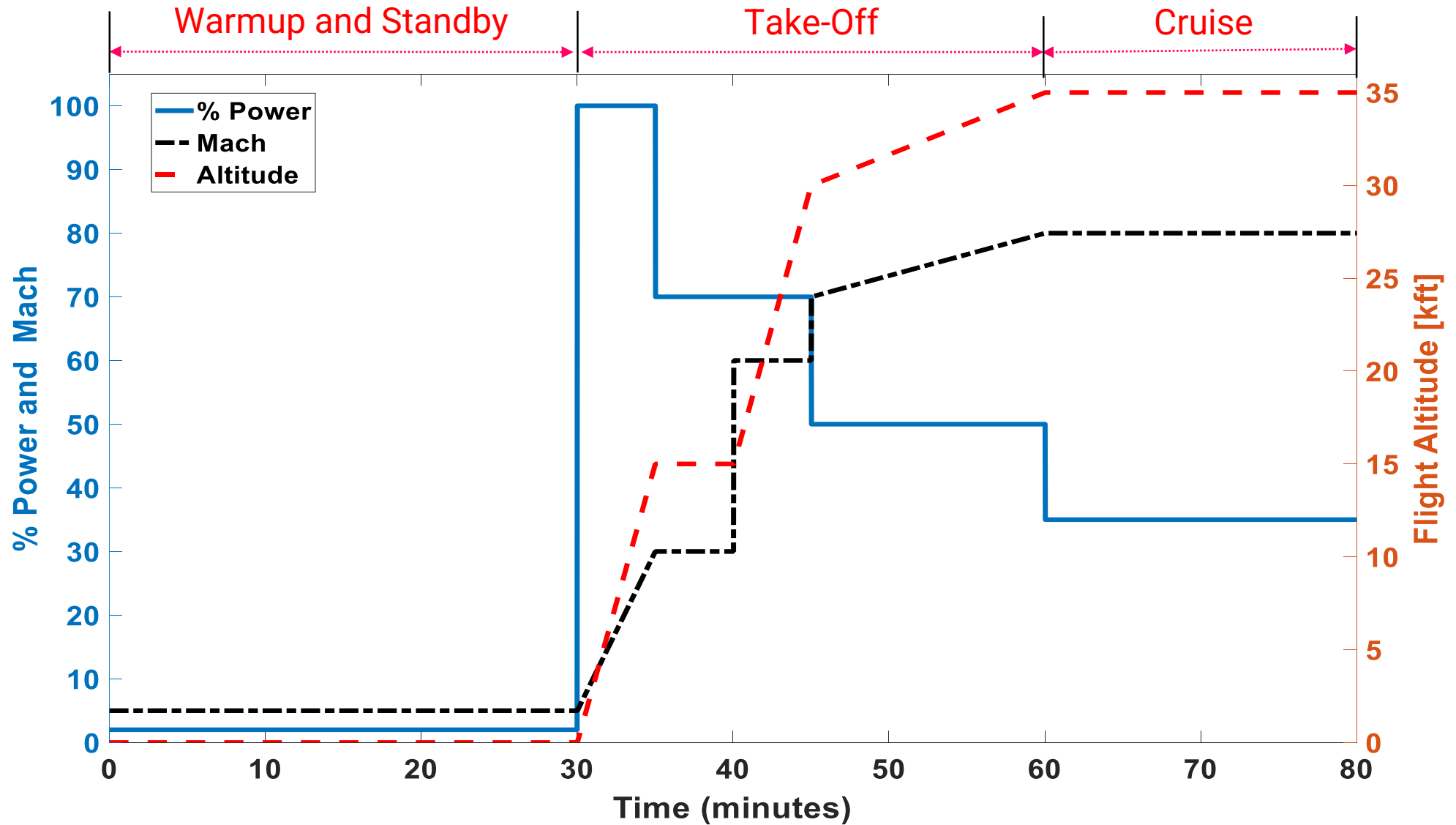
**Results are preliminary, sizing parameters and vehicle controls need further refinement**

# Simulated Warmup Compared to Measured Data

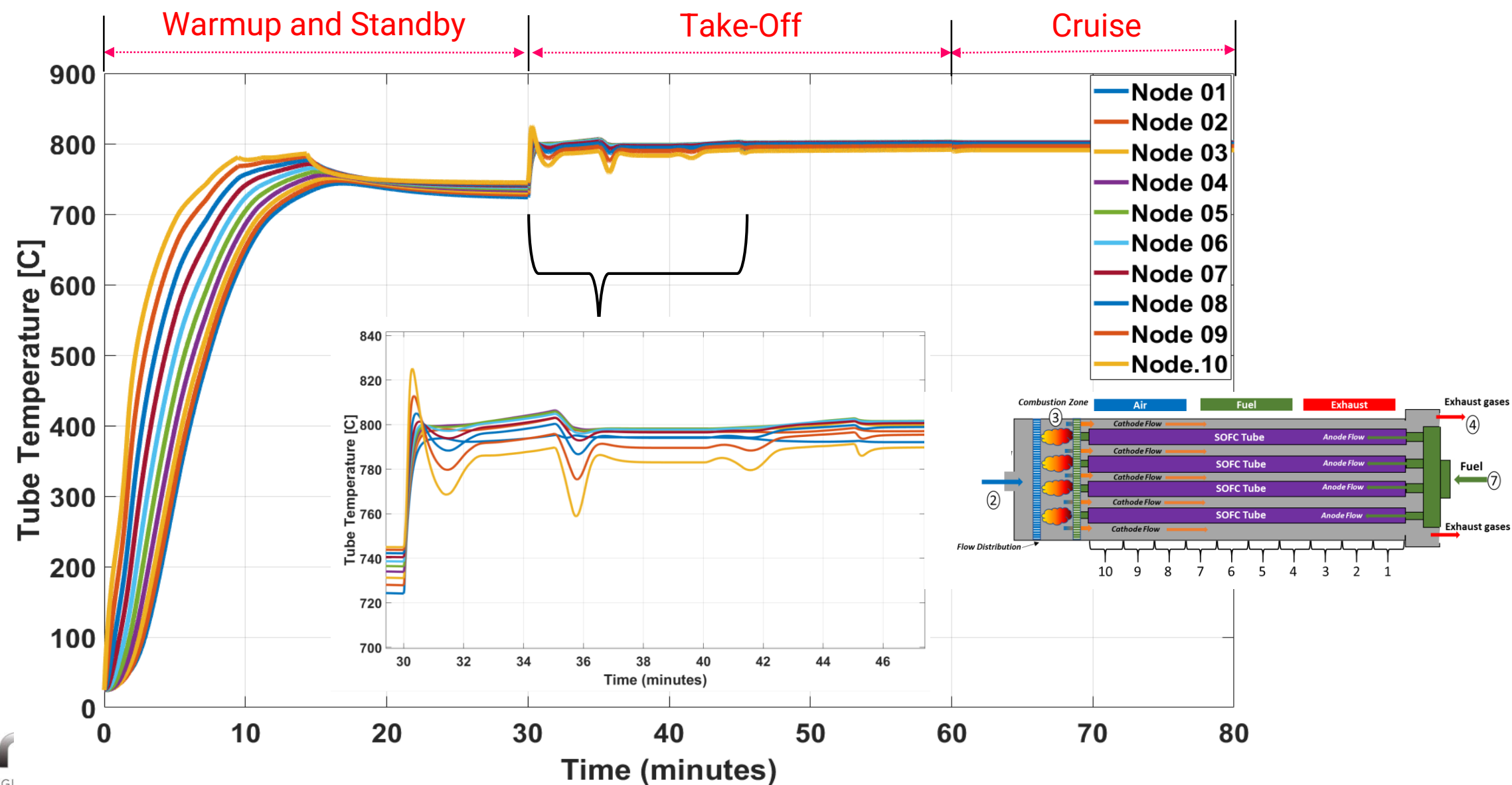
- ▼ The ESPG dynamic model was modified to account for corrected air flow and SOFC mass to parametrically match a 1,000 W commercial Special Power Sources SOFC unit.
- ▼ The dynamic model was able to predict the warmup sequence.
- ▼ 60 minutes was required for this warmup, but < 20 minutes has been demonstrated with commercial units in the field.



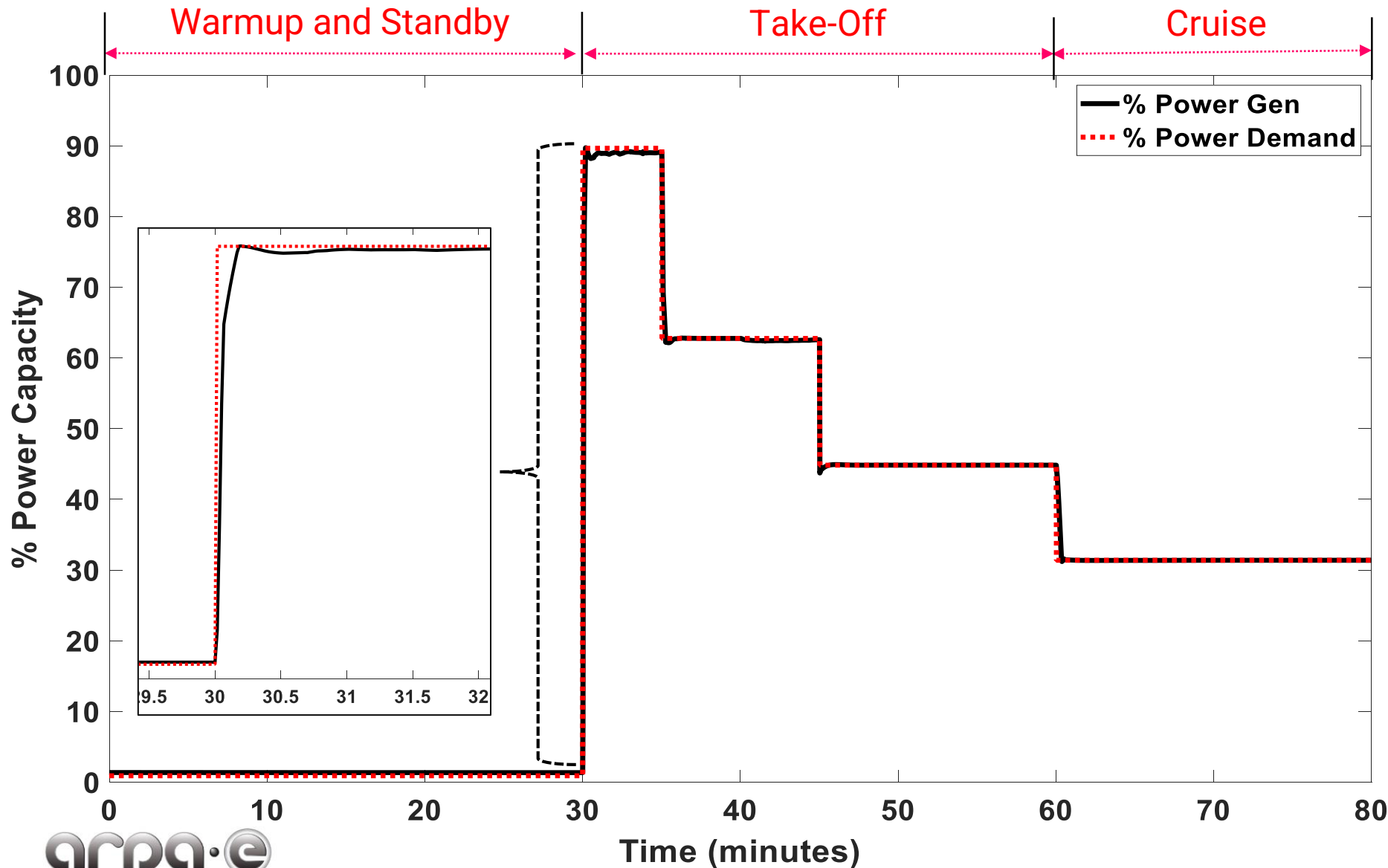
# Notional Flight-Simulation



# Simulated SOFC Stack Warmup

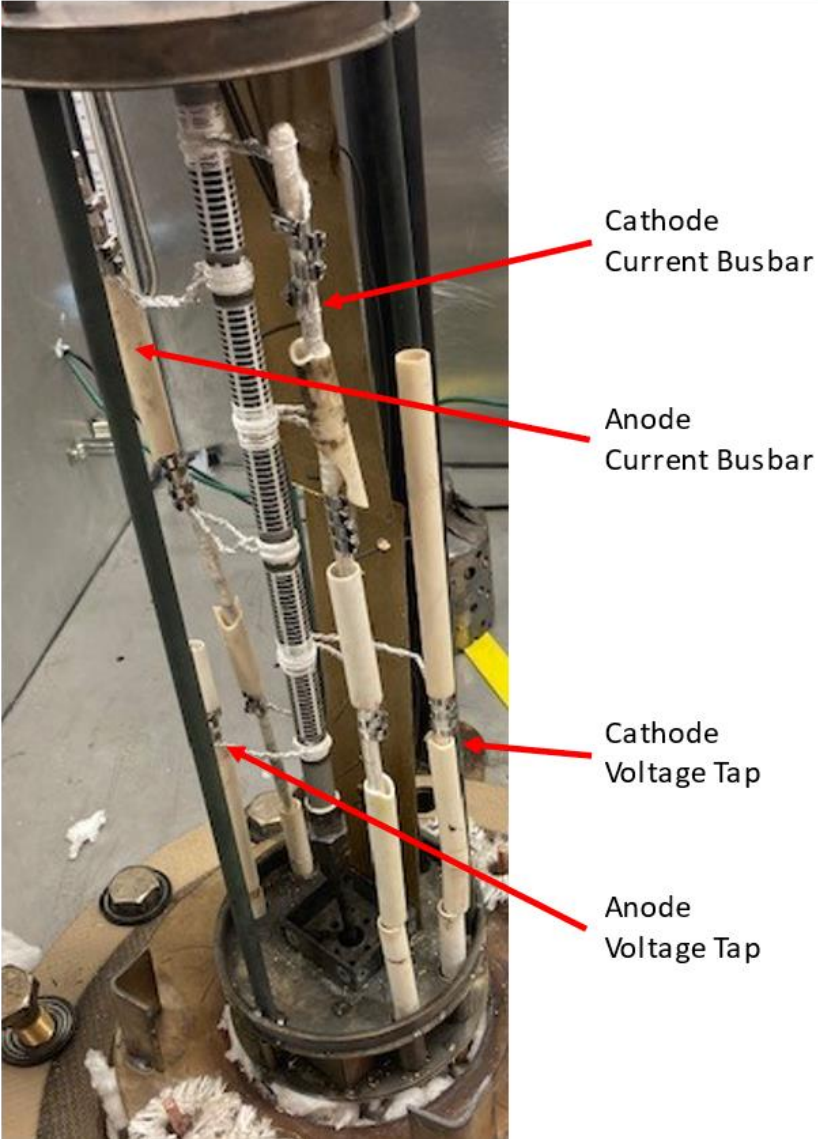
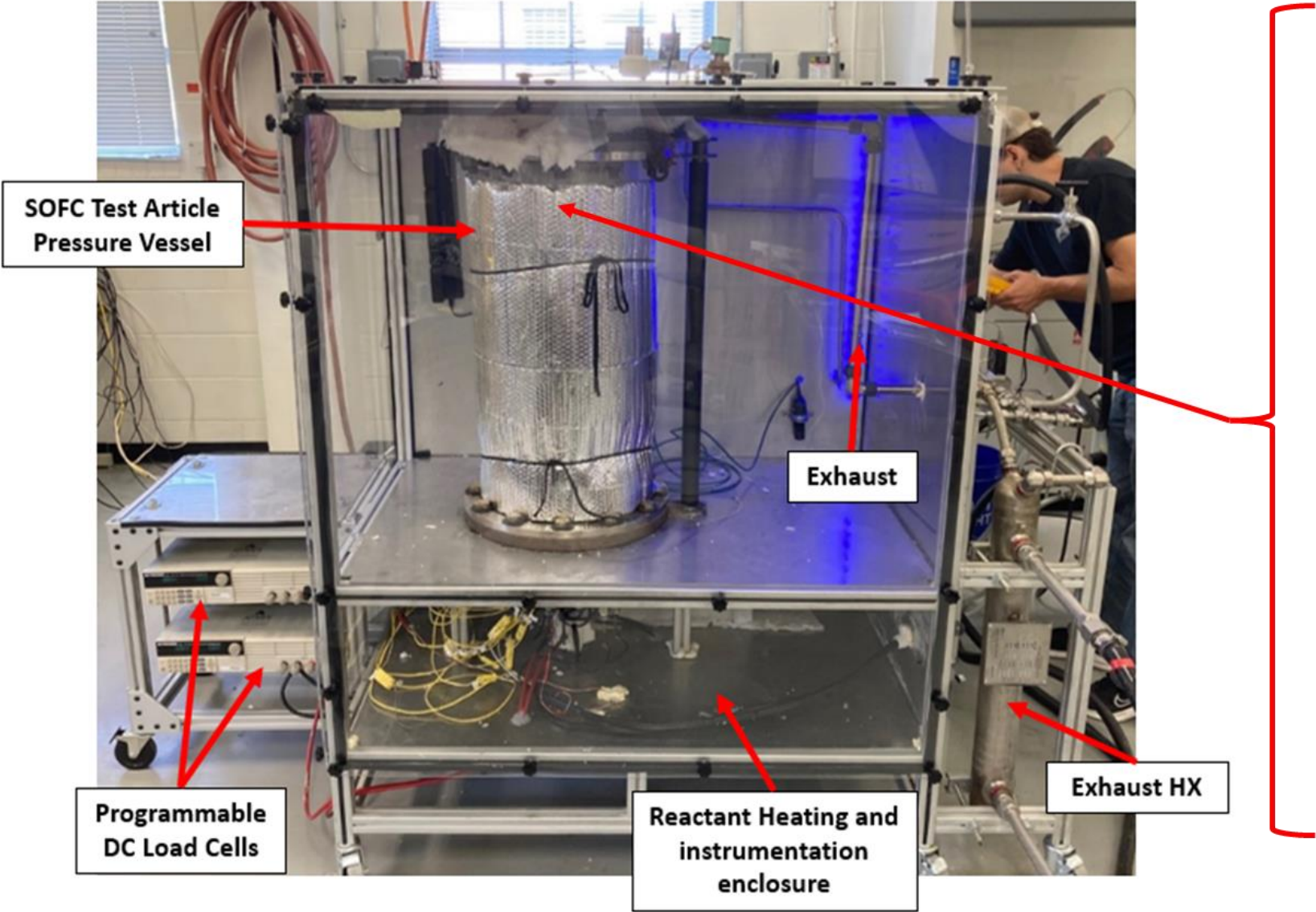


# Simulated ESPG Power Load Follow



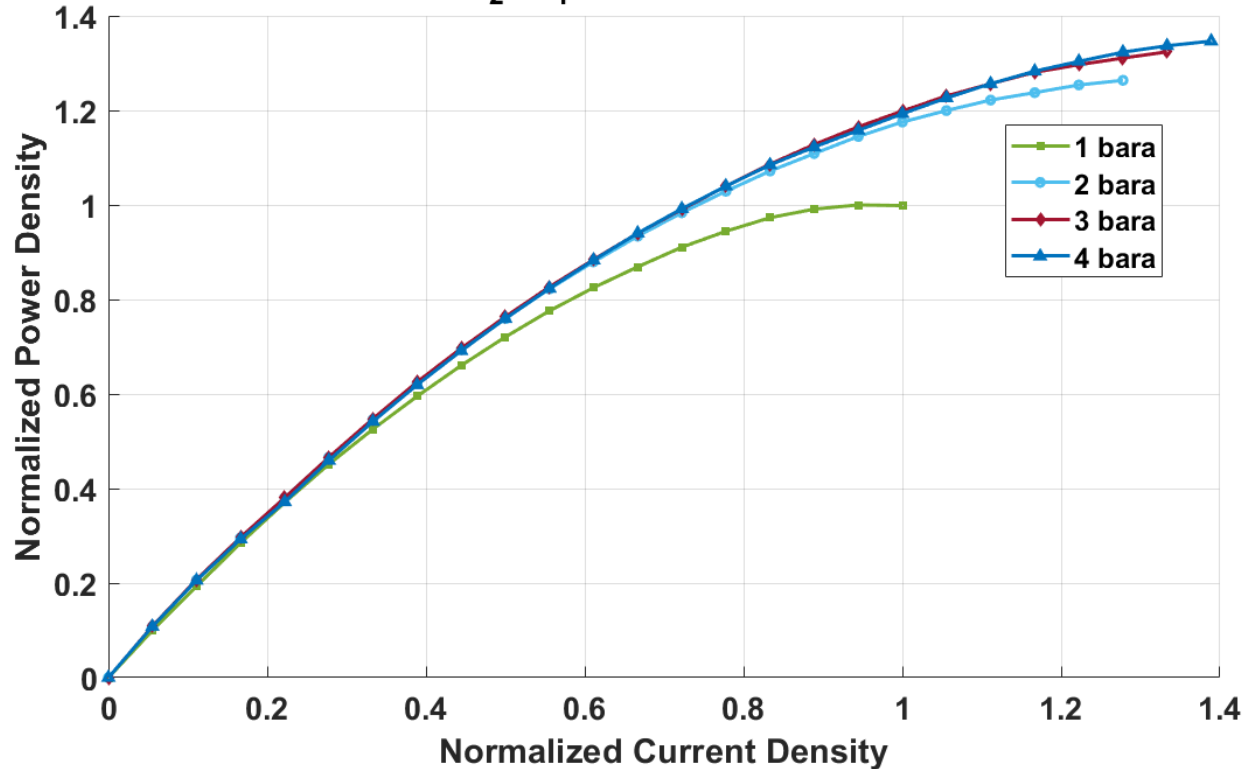
- ▼ The ESPG system was able to meet the dynamic vehicle electrical load demands, 90% step change in 1 minute
- ▼ Small battery storage (100 kW-hr) would be required to meet the large step change in power demand (worst case)

# SOFC Pressurized Testing



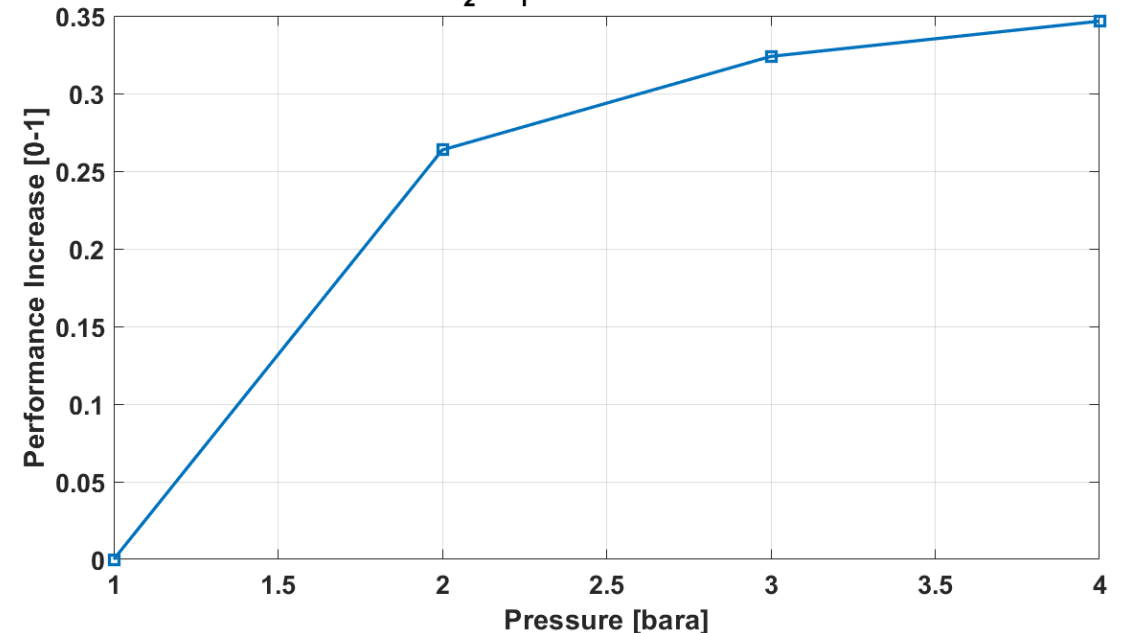
# Anode Supported SOFC Pressurization

SOFC Pressurization  
 $H_2$ ,  $U_f = 0.50$ ,  $T = 750^\circ\text{C}$



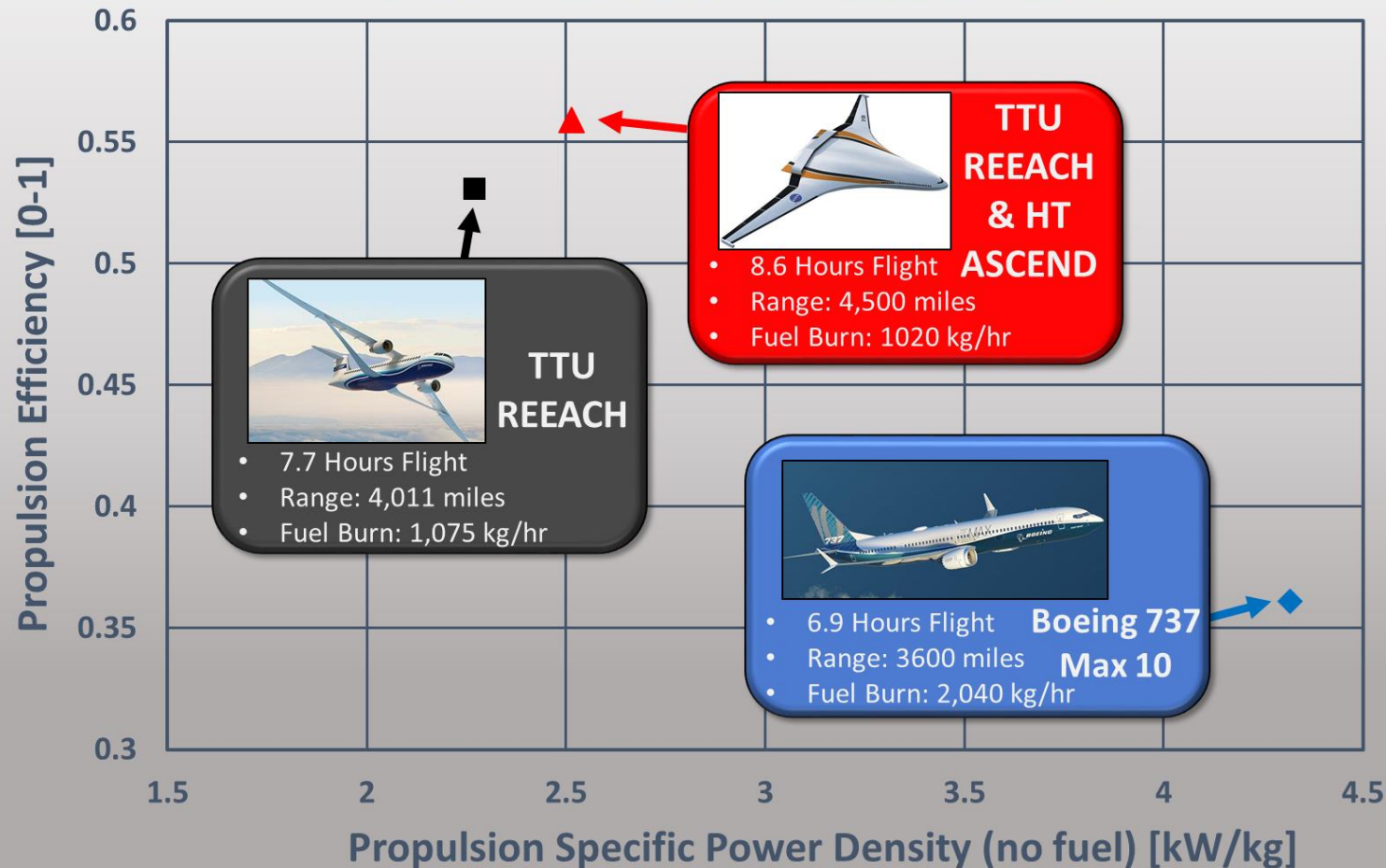
- ▼ SOFC performance was normalized using the peak ambient power density and current density
- ▼ 35% increase from 1 to 4 bara

SOFC Peak Performance Increase  
 $H_2$ ,  $U_f = 0.50$ ,  $T = 750^\circ\text{C}$



# Summary of REEACH Comparison State-of-Art

REEACH COMPARISON TO STATE-OF-ART



## Assumptions:

- Power Gen. Thermal efficiency – 65%
- Power Gen. Specific Power – 3.6 kW/kg
- Bio LNG for REEACH, Jet A for 737 Max

## TTU REEACH

- Motor drive specific power -127 kW/kg
- Motor specific power – 12 kW/kg
- Motor efficiency – 93%

## TTU REEACH & HT ASCEND

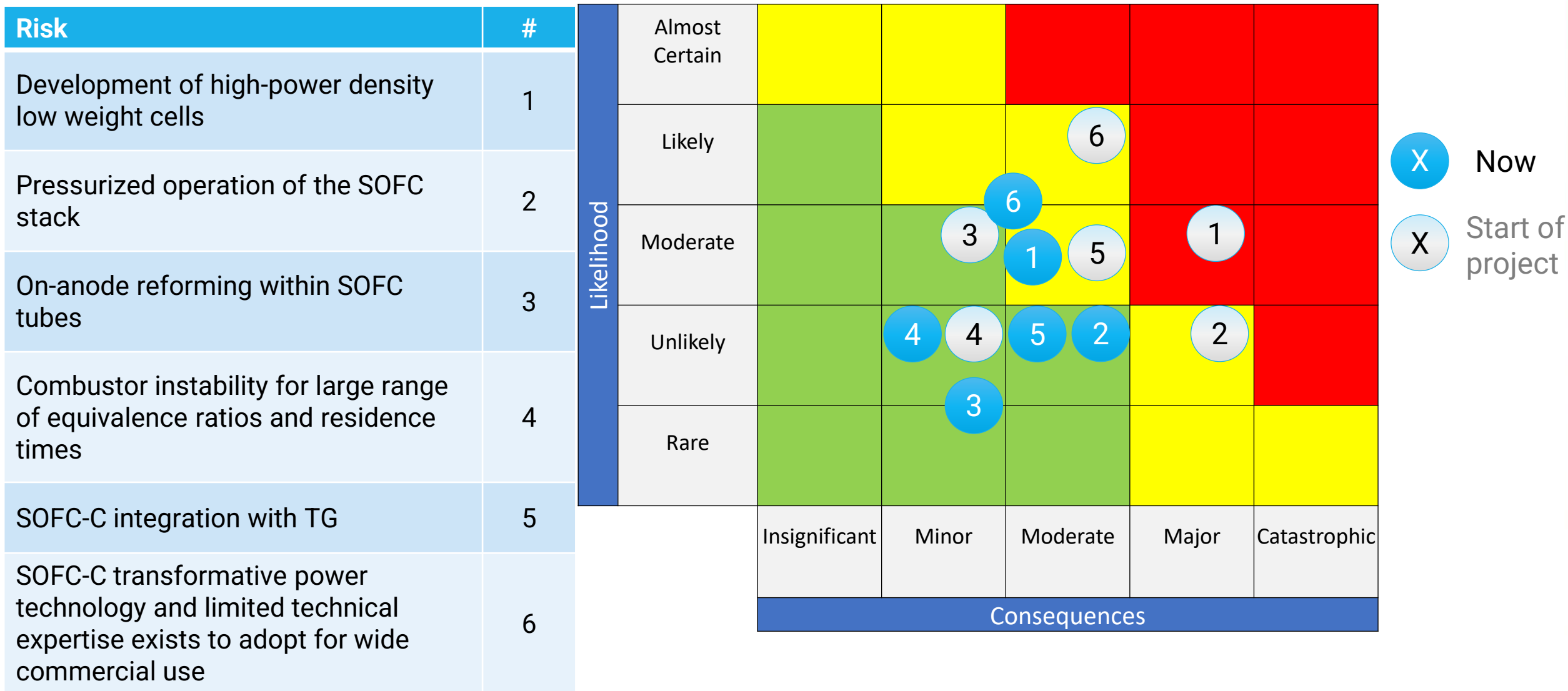
- Motor drive specific power -127 kW/kg
- Motor specific power – 20 kW/kg
- Motor efficiency – 98%

# ***Task Outline & Technical Objectives***

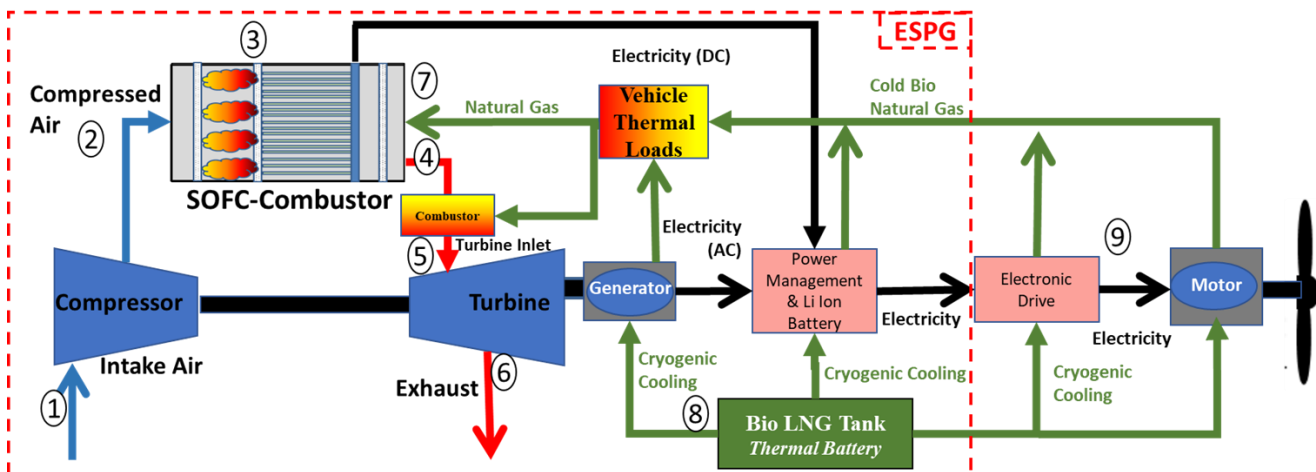
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- ▶ Phase 1 Objective: Demonstrate 1 kW SOFC-C operating within the boundary conditions of a ESPG designed to exceed state-of-art propulsion
- ▶ Task 1: Task and Milestone Negotiation/Project management
- ▶ Task 2: ESPG System Design
- ▶ Task 3: Single Tube Development
- ▶ Task 4: Multi-Tube SOFC-C Bundle Development
- ▶ Task 5: Technology to Market
- ▶ Phase 2 Objective: Demonstrate 5 kW SOFC-C operating within the boundary conditions of a ESPG designed to exceed state-of-art propulsion

# Risk Update



# REEACH 2240-1541 T2M Commercialization Plan – Jun 2022



## Team Plan to Commercialization

- Planned Business Model is internal business unit with SPS lead
- Business Plan drafted and being internally reviewed
- Freedom to operate analysis underway

### Anticipated First Markets:

#### Product/Service

- 1) SOFC-C or EPSG Configuration

#### Description

- 1) UAV – Group 4 i.e. MQ-1
- 2) Regional Aircraft – <75 seat Electric Aircraft
- 3) Light Air Cargo – UPS/medical products and military

#### Pricing Strategy

- 1) SOFC-C or EPSG Configuration – Fixed Price PO with margins set by market conditions

### Anticipated Long-Term Markets

#### Product/Service

- 1) SOFC-C or EPSG Configuration

#### Description

- 1) Commercial Aircraft – 186 seat Electric Aircraft

#### Pricing Strategy

- 1) SOFC-C or EPSG Configuration – Fixed Price PO with margins set by market conditions

### Anticipated Services/Spares

#### Product/Service

- 1) SOFC-C or EPSG Configuration Service Contracts and Spares

#### Description

- 1) Commercial Aircraft, Regional and Light Air Cargo

#### Pricing Strategy

- 1) SOFC-C or EPSG Configuration – Regional Service & Spares Distribution Centers

# Needs and Potential Partnerships

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- ▶ **Needs project has currently:**
  - Contact with airline customer for establishing customer needs
- ▶ **Anticipated needs following the completion of the award:**
  - Application of RTX generator capability to develop a multi-megawatt machine, not being addressed in this program
  - Power electronics to integrate and regulate voltage and current from SOFC and generator.
  - Infrastructure expertise related to aviation flight support
- ▶ **Capabilities that could be useful for other REEACH teams:**
  - Integrated propulsion, power, and thermal management expertise
  - Pressurized SOFC operation expertise
  - LNG for aviation fuel expertise

# Q & A



U.S. DEPARTMENT OF  
**ENERGY**

<https://arpa-e.energy.gov>